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Smart Solar Panels: In-situ monitoring of photovoltaic panels based on wired and wireless sensor networks

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Abstract

This article presents the design methodology for an in-situ solar panel monitoring system based on wired and wireless sensor network technologies. The system presented provides in-situ performance data for each solar panel of a solar park installation and allows through a web-based application the optimization of electric power production. The proposed platform is based on wired networking technologies combined with short range low-power wireless sensor nodes. Performance parameters are measured for each PV panel and are transmitted to a remote coordinator. Details about the developed platform are presented with preliminary results.

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1. Introduction

The electric power grid in most countries is in a large extent old, centralized and based on non-renewable energy sources as coal. Today, regulatory requirements are calling for sharp reductions in carbon dioxide and greenhouse gas emissions footprint from the energy sources utilized, therefore the widespread use of renewable energy sources is mandatory [1,2]. Grid-tied photovoltaic (PV) Distributed Power Generation Systems (DPGS), especially roof and ground-mounted, are today becoming very

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important. In addition, the evolution for a smart grid using the Autonomous Metering Infrastructure (AMI) fuses computation communication and sensing technologies for providing decentralized energy management.

Solar energy is the most abundant renewable energy source and today there is a large interest for its use globally. The cost reduction of solar cells together with governmental policies will accelerate the use of grid-tied photovoltaic systems in commercial, residential and industrial applications. The solar cell manufacturing technology is continuously improving, however the use of optimization techniques for solar power production, monitoring and management is not following the same pace. Two main directions are followed right now in the PV Industry for optimization of energy production with the introduction of commercial products. In the first one microinverters are used in each solar panel and the energy is delivered with an ac voltage bus [4, 5, 6]. In the second approach DC/DC optimizers are placed in each individual panel [6, 7, 8] and are communicating with a central coordinator for MPPT (Maximum Power Point Tracking) optimization. An interesting variation proposed recently [9] utilizes a DC/DC high voltage converter integrated in each PV panel and synchronized with a central coordinator for MPPT optimization. With this approach Energy is delivered through a parallel connection to a High Voltage Bus, resulting to small diameter cables. What is evident from the topologies that are based on DC/DC converters is that the need for bidirectional communication with a central control unit for MPPT optimization becomes very important.

The efficiency of a PV panel is seriously affected by sunlight irradiance blocking obstacles, dirt accumulated in the solar panel protection glass as well as field-aged degradation [10-12]. Aging effects of PV cells affects the I-V characteristics, so an in-situ measurement system of PV performance characteristic parameters can provide valuable information for optimized power generation. What is known from field studies is that the most degraded modules have no correlation between visual defects and performance [13]. The PV panels are normally tested in the production factory once and in standard conditions, with the cost of dismounting from an installation fixture and testing them to be always prohibitive. Consequently, each solar panel is usually left unattended during its production life, thus resulting to sub-optimal electric power generation with considerable cost. On the other hand, the convergence of informatics and communications with ongoing advances in microcontrollers and CMOS RF-transceivers are the enabling technologies for the use of low cost wireless sensor networks for monitoring and characterization of the PV panels in the field. The need for a continuous preventive maintenance procedure for PV generators based on a distributed monitoring and testing device is obvious [14, 15].

In this paper a design methodology is proposed, that provides the in-situ characterization of individual PV cells based on wireless sensor networks and the transfer of data to remote computers with web-based technology. The methodology proposed is suitable to solar topologies where each PV panel is optimized autonomously from the other panels in a parallel or serial (string) arrangement as depicted in Fig. 1. Topologies of this kind are utilizing inverters (microinverters) connected to each PV panel and with a parallel arrangement to the grid. Alternatively optimizers are used in every PV panel and a string connection is followed that feeds a central inverter. These topologies offer certain advantages in the cases of shadowing or performance deterioration (due to aging, dirt etc.) of individual solar panels.

In the following sections an overview of the sub-system modules developed is given. First the main parts of the proposed system are presented, followed by an analysis of critical issues concerning the scalability of such a characterization and optimization architecture that is based on wired and wireless networking technologies. Finally, preliminary experimental results are presented.

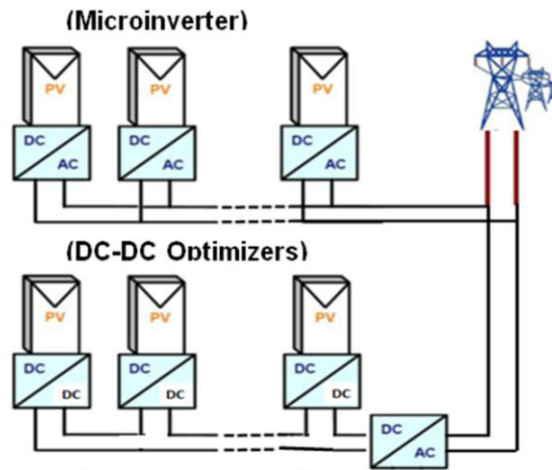


Fig. 1. Optimization Architecture based on Micro Inverters and DC/DC optimizers

2. Architecture of the PV-panel monitoring and characterization platform

2.1. System Architecture

In Fig. 2 (a) the overall system architecture is given. A three-tier architecture has been followed for the monitoring and characterisation system, with the first level referenced to the characterization module of the PV solar panel, the second level referenced to the PV cluster gateway, with the third level to be referenced to the PV park coordinator and the web-based communication technologies with remote monitoring and control computers.

In the first level a characterization device is embedded in each PV panel (**PV characterization module**), which integrates a microcontroller with the associated electronics for control of the overall procedure and support of communication with a local gateway through a **serial bus**. The embedded microcontroller in the PV panel characterization device realises a miniature data acquisition system [16-18]. The local gateway supports bidirectional communication through a wired serial communication bus with a number of PV panels that belong to a group (called cluster hereafter) with similar insolation characteristics (orientation and shading from various objects) and manufacturer specifications. Moreover the gateway provides wireless communication services for the PV cluster using WSN networking technology with a central remote PV park coordinator.

With the proposed architecture characterization data from the PV panels are transferred to remote clients using free web publishing services like Cosm [19]. In the reverse direction the capability of sending control data to the PV panel embedded microcontroller for monitoring and “triggering” of the characterization procedure is also supported via simple server-client commands.

2.2. PV panel Characterization procedure

In Fig. 2 (b) the flow of the control and monitoring data for the characterization procedure of the PV panel is presented. As the characterization procedure of each individual PV panel uses the existing solar

radiation it is critical to synchronize each PV panel measurement unit with the similar PVs of the cluster. With this approach the characterization procedure for each cluster of PV panels is based on similar solar irradiation conditions. Such a grouping of PV panels is a common practice in PV installations especially on roof tops of houses where specific PV panels have identical orientation and can form PV clusters.

The characterization procedure starts with the electric isolation of each individual PV panel from the PV panels of the cluster through an electromechanical relay. When the relay is activated the PV panel is electrically isolated from the other panels of the PV cluster and the characterization procedure can be started. The voltage and current signals are digitized by the 10-bit ADC which is embedded in the microcontroller used. After the characterization procedure the I-V data collected are transferred through the LIN bus to the PV cluster gateway and then wirelessly to the PV park coordinator for web publishing.

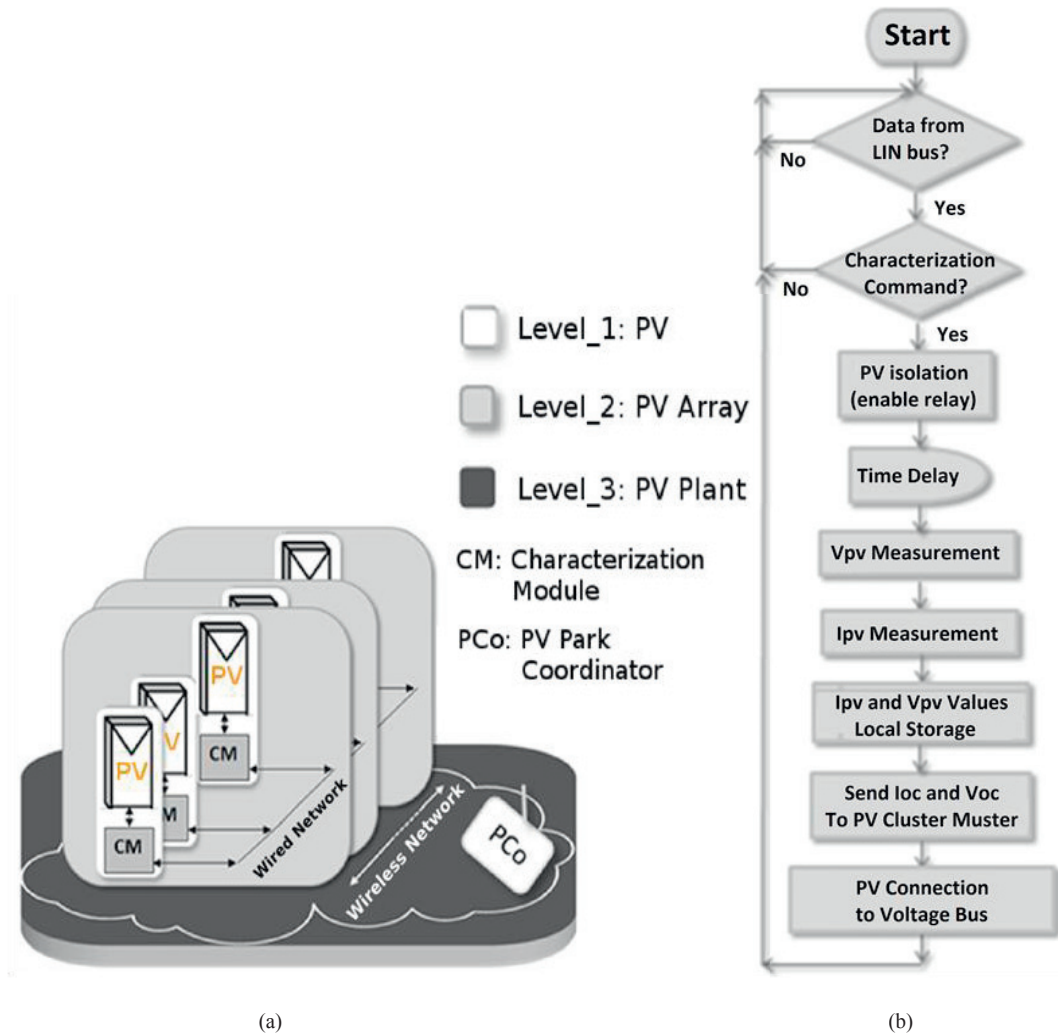


Fig. 2 (a) The proposed three-tier architecture, (b) Flow of control data for the PV panel characterization procedure

2.3. Embedded networking platform for characterization and monitoring of PV panels

For realizing the described PV cell characterization architecture a basic platform has been developed with two variations for the characterization module and the cluster gateway. These variants have a common basic microcontroller board with different communication and sensing capabilities. The PV characterization module has embedded LIN (Local Interconnect Network) slave capability, while the PV cluster gateway integrates a LIN master for serial communication with the members of the PV cluster together with WSN technology for wireless communication with the PV park concentrator. The PV park coordinator is based on the Arduino open source platform that realizes a WSN coordinator for wireless communication with all the PV clusters gateways and supports web technologies for communication with a remote server.

The basic platform developed (named ZL01-Node) has a small form factor and is based on a reconfigurable System On Chip (SOC) microcontroller and an embedded wireless sensor network RF modem. This platform can be embedded in the PV panel and support the automated data acquisition and control of the characterization procedure for the collection of panel operational data without the need of panel dismounting [13]. Two variations of this platform have been developed that are based on the same microcontroller and the only differentiation is the communication capabilities which determine the role of each one. According to what was described in the previous paragraph each cluster gateway integrates a LIN master and wireless sensor networking technology for communicating with the LIN slaves of the PV characterization modules and the Park coordinator respectively.

For the bidirectional wired communication with the cluster gateway two serial bus standards have been considered for the physical layer, the RS-485 and the LIN standard. The LIN bus is used in the automotive industry at the lower level for controlling various loads in cars, like window controls, seat movement, mirror positioning and LED lighting [20]. The LIN bus has been selected for its simplicity and low cost, which are mandatory issues for medium to large scale PV installations. Its widespread adoption from the automotive industry has resulted to extremely low cost LIN drivers for LIN master and slaves devices. The communication protocol is based upon the Universal Asynchronous Receiver/Transmitter (UART) data format that implements a single-master/multiple-slaves concept. The main characteristics of the LIN bus are its Low-cost single wire implementation (with the assumption that the ground connection already existed for electric power transfer) together with the self-synchronization capability without a quartz resonator in the slave nodes, the extended range of power supply input with single polarity, instead of the more complex power supply distribution of the EIA-485 standard. By comparing the LIN bus with the EIA-485 standard a number of advantages for the LIN bus are evident, like simplicity, the utilization of a single wire instead of the two differential pairs for the RS-485, the integration of a DC/DC converter in the LIN driver, the wide range for the supply voltage and the extremely low cost. According to the LIN addressing specifications 15 LIN slaves can exist in the same bus, with possible extensions for addressing more devices using appropriate software. Concluding the scheme followed supports the direct addressing of up to 15 LIN slaves for a PV cluster and this topology can be repeated accordingly for the PV park installation with the addition of cluster gateways.

For either of these variations the same Node platform (named ZL01 and depicted in Fig. 3) has been realized based on a PSoC (Programmable System on Chip) microcontroller from. The integrated Zigbee communication technology is based on a Zigbee RF modem available from ATMEL. It provides the full Zigbee PRO certified stack for wireless communication at a maximum 3dBm RF output power that is adequate for 50-60 meters range of node to node wireless communication. The Zigbee technology is supported by most of the larger IC manufacturing companies and is in widespread use today for a large variety of applications [21]. We have selected the Zigbee standard for the wireless sort range

communication between the cluster gateway and the PV park coordinator, because of its low cost, maturity and its widespread use in WSNs.

For the characterization of the panel an electronic load has been embedded in each PV panel and controlled from the embedded microcontroller platform, together with the associated relays necessary for panel electric isolation and the electronics for voltage and current measurements. In the following paragraph details about these electronics are given.



Fig. 3 ZL01-Node – The embedded data-acquisition wireless node for PV panel characterisation

2.4. Electronic load and electric isolation electronics

The performance characterization of the PV panel is normally performed through I-V curve measurement in standard conditions (Irradiance of 1000 W/m^2 @ 25°C). The methodologies followed for fast field testing of PV panels are normally based on one of three techniques [17, 18]. In the first technique a variable resistance is used, in the second one a capacitor charging methodology is followed, while the third one relies on an electronic load digitally controlled.

We have selected the third technique for panel characterization with the development of a simple low cost electronic load. In the realization described the performance parameters I_{sc} V_{oc} are measured at specific insolation conditions. As is well known, the I-V characteristic of a PV panel depends on temperature and irradiance so sensors are used for their measurement. Temperature and humidity measurements of the PV panel are based on a smart sensor (SHT11) manufactured by the Sensirion Co. and under the control of the PV embedded microcontroller. A photodiode is also used for the measurement of the irradiance level. The key idea for characterizing PV panels with the proposed system is that groups of PV panels (called PV clusters) has the same orientation and are manufactured from the same company. Therefore for successful intercomparison the characterization procedure must be performed simultaneously for all the PV panels of the cluster.

As already referenced previously, an electromechanical relay is used, that provides the electric isolation of the PV panel before the characterization procedure [22]. The electronic load developed uses a voltage regulation technique for measuring the I_{sc} current of the PV panel [16, 23] and is presented in Fig. 4. The microcontroller of the characterization module measures with its embedded ADC the current (I_{pv}) through a sensing resistor R_1 , while the voltage (V_{pv}) of the PV panel is measured after an attenuator circuit (not shown in Fig. 4). The load developed uses a MOSFET that is controlled through

the applied VGS voltage from the comparator output. The microcontroller provides a reference voltage (V_{REF}) that drives the U1A comparator that determines through the V_{GS} gate voltage of the MOSFET the I_{DS} and consequently the current supplied by the solar panel. The circuit of Fig. 4 follows a voltage regulation scheme where a shunt resistor R1 is in series with the Q1 IRFP150N MOSFET. The voltage sensed from the R1 is directed to the comparator and the ADC input of the microcontroller. The I_{pv} current sensed is determined from R1 as $I_{pv} = I_{DS} = V_{R1}/R1$. The procedure that is followed starts with a V_{DS} close to V_{OC} and is continuously reduced in predetermined steps through the V_{REF} voltage from the microcontroller until the sensed current is approximately constant. When the above referenced condition is met the sensed current is considered as the short circuit current I_{SC} . This low-cost circuit has therefore limitations for measuring the part of the I-V characteristic where the current is almost constant and as a consequence small voltage changes in the MOSFET V_{GS} results to large current changes. The ADC resolution determines the minimum error for the current and voltage measurements.

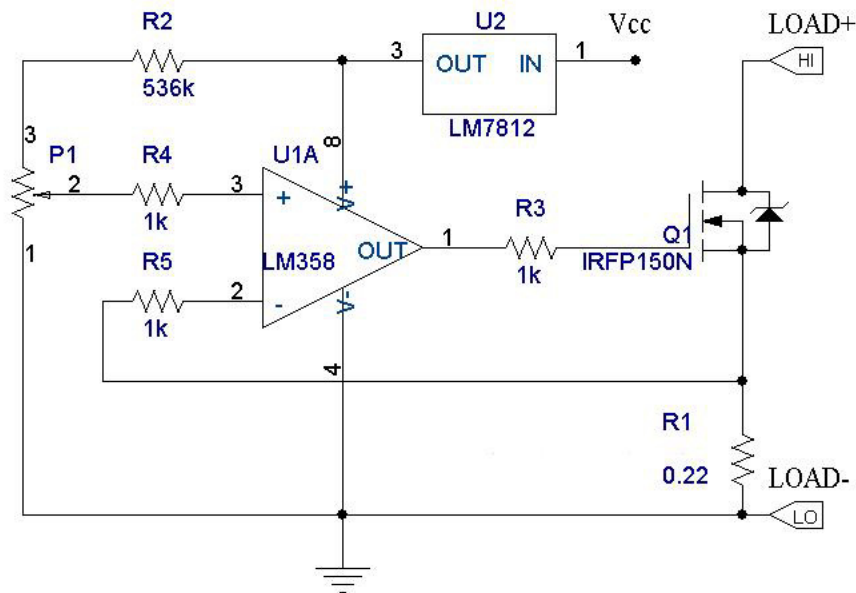


Fig. 4 Schematic diagram of the Electronic load used for I-V measurements

3. Open Software /Hardware coordinator platform for the web-based remote monitoring and characterization of PV panels

The distributed power management of the electric power produced from small renewable source generators demands the use of new technologies for monitoring [4, 5]. However, these solutions cannot be easily adapted to the rapid evolution of wireless sensing standards for measurement and web-publishing technologies. On the other hand, open source software solutions can be easily modified and adapted to the technology trends enabling further research in the associated scientific fields.

The Park coordinator belongs to the third layer of the proposed architecture which provides monitoring services by communicating wirelessly with the clusters gateways and web-publishing services through a client-server topology to a remote control computer. The development of the coordinator device has been

based on an open source hardware platform, Arduino, while the client-server web-publishing software has been based on the open-source Cosm platform [10]. Cosm is an open source platform, suitable for the internet of things envisagement, for transmitting and receiving real-time sensor, energy and environment data from objects, devices and buildings, through the internet using “feeds” (data type that contains a collection of sensor data streams). Using the Cosm API (Application Programming Interface) one can input data to monitor and visualize them in graphs simply by updating a feed, or use a feed's output to control remote devices and environments with the use of “triggers”. The Cosm API uses the REST architecture, that is, it supports HTTP requests like GET, POST, PUT or DELETE making the client interface simple and bandwidth efficient. The data formats supported for client requests are the Extended Environments Markup Language (EEML), JSON and comma-separated values (CSV).

There are two ways of sending data as input to Cosm, the automatic and the manual one. With the automatic mode, servicing requests from Cosm are allowed every 15 minutes or whenever another client requests them, with the use of Arduino's Cosm library. In the latter case, Cosm reads the EEML document that includes the sensor data and meta-data. In the manual mode the data are uploaded from the client to Cosm. The default rate limit for requests (post new data or access history data) to Cosm API is 100 requests every minute. Cosm can return data to the client when previously set conditions are met, all of which are stated in a “trigger”. Triggers send HTTP POST requests to a URL chosen from the client through the Cosm API or created from the web interface. All the needed information is located inside the request's body. To extract the desired data, a script has to deal with this request. The minimum interval between sending out two different notifications is 5 seconds.

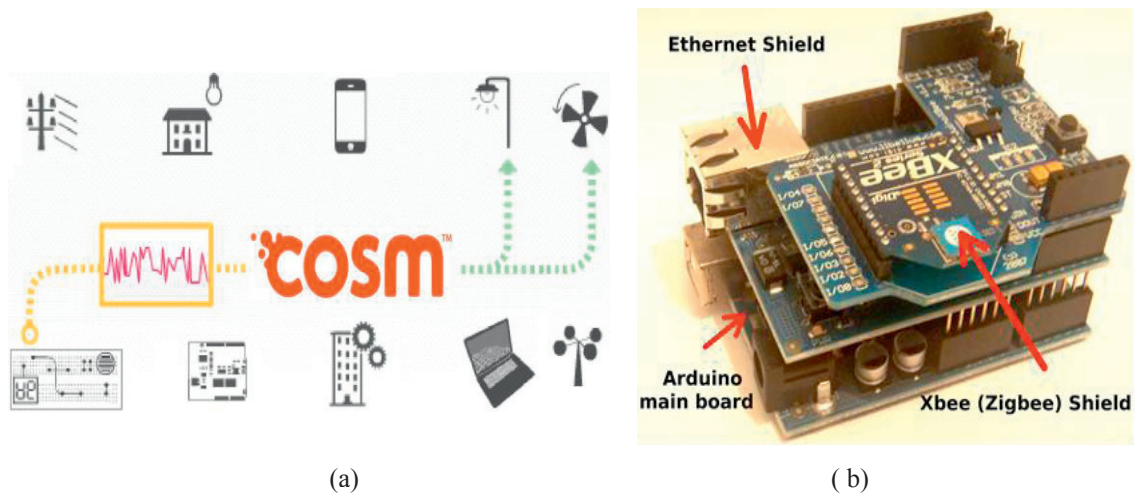


Fig. 5 (a) The Cosm “ecosystem” [10], (b) Photo of the Arduino-based PV park coordinator

The hardware of the Park coordinator is based on the Arduino platform and support web connectivity with a remote computer together with wireless Zigbee connectivity with the Park gateways [24]. The Arduino's hardware features are extended by simply connecting its “shields” (stacked boards) on top of it. An Xbee Shield is used in the described application that allows the deployment of a Wireless sensor network with the Arduino board to play the role of the host node that communicates wirelessly over the Zigbee protocol with the PV clusters gateway and through the local LIN buses with all of the PV panels.

In addition an Ethernet Shield is used which allows the board to connect to the Internet through an ADSL router and support client-server services.

The Cosm API supports also DHCP, to establish a network connection without the need of hard-coding the IP address. In the current implementation the Arduino platform is used to publish data to the Cosm platform and to handle the “triggers” that the user has previously set.

The free and open source Cosm and Arduino platforms resulted to a low-cost PV park coordinator that supports two-way wireless communication with the PV panels and web connectivity with remote computers. The number of panels supported is limitless, while capability of integration of geographical data in the Cosm platform provides a natural way of managing the PV park installations.

4. Preliminary PV characterization measurements

Preliminary measurements of performance parameters of a small PV panel are presented in the graphs (a) and (b) of Fig. 6. The measurements were extracted in the laboratory for two different illumination conditions, with the two curves of Fig.6 (a) revealing an expected behaviour.

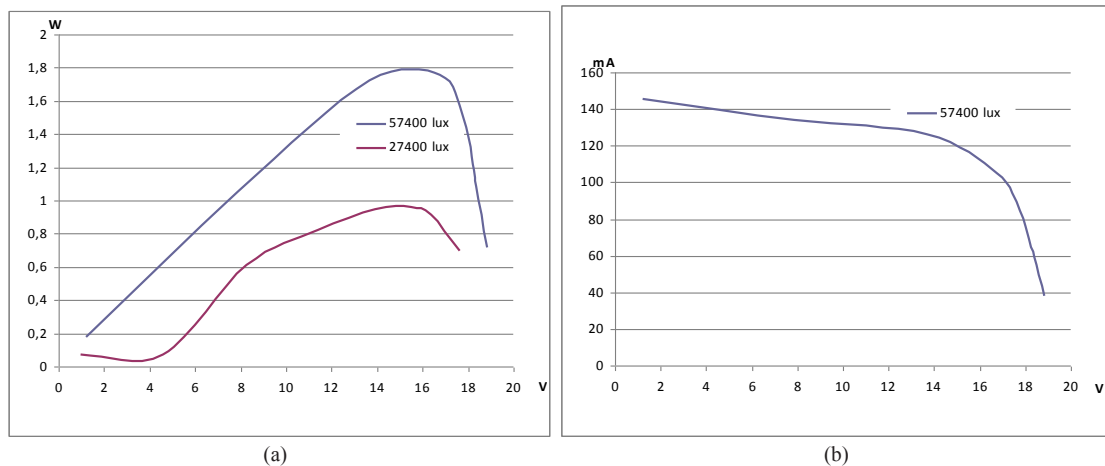


Fig. 6 (a) PV panel Power measurements for different irradiance conditions, (b) PV panel I-V measurements

5. Conclusions

The methodology demonstrated in this article fuses computation and communication technologies for real-time monitoring and characterization of PV panel operational status. The use of wireless sensor network technology provides low complexity and cost communication with a coordinator, while new web-based publishing technologies simplify the design, maintenance and operation of large networks of PV panels. By grouping of the PV panels in clusters and the use of the **single wire LIN bus** the complexity of the network deployed is kept at the minimum. The architecture proposed is fully scalable with the number of PV panels and takes advantage of open-source platforms for web-publishing of characterization data at a low-cost. Panels with efficiency changes due to aging or other effects can be identified through the proposed in-situ characterization system and the owner will be informed in real-time for maintenance actions and possible guarantee claim.

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